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ISOSPIN CONSIDERATIONS IN CORRELATIONS OF PIONS AND B MESONS

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ABSTRACT

The correlations between a B meson and a pion produced nearby in phase space should respect isospin reflection symmetry $I_3 \rightarrow -I_3$. Thus, one generally expects similar $\pi^+ B^0$ and $\pi^- B^+$ correlations (non-exotic channels), and similar $\pi^- B^0$ and $\pi^+ B^+$ correlations (exotic channels). Exceptions include (a) fragmentation processes involving exchange of quarks with the producing system, (b) misidentification of charged kaons as charged pions, and (c) effects of decay products of the associated \bar{B} . All of these can affect the apparent signal for correlations of charged B mesons with charged hadrons. The identification of the flavor of neutral B mesons through the decay $B^0 \rightarrow K^{*0} J/\psi$ requires good particle identification in order that the decay $K^{*0} \rightarrow K^+ \pi^-$ not be mistaken for $\bar{K}^{*0} \rightarrow K^- \pi^+$, in which case the correlations of neutral B mesons with hadrons can be underestimated.



I. INTRODUCTION

It has recently been suggested [1] that one can identify the flavor of a neutral B meson at the time of production through its correlation with a charged pion produced nearby in phase space. If such correlations are found, one has a useful means of studying CP-violating rate asymmetries in the decays of neutral B mesons to CP eigenstates like $J/\psi K_S$.

In order to calibrate the effectiveness of this method, one can study the correlations between charged pions and B mesons of *known* flavor. Most decay modes of neutral B 's, such as $B^0 \rightarrow D^{*-} \ell^+ \nu_\ell$ and $B^0 \rightarrow K^{*0} J/\psi$, provide flavor information. However, the reconstruction of a B is hindered by the absence of the neutrino in the first case, while in the second there is the potential of confusing the decay $K^{*0} \rightarrow K^+ \pi^-$ with $\bar{K}^{*0} \rightarrow K^- \pi^+$ if particle identification is not efficient.

The flavor of a charged B is inferred directly from its decay mode, such as $J/\psi K^\pm$. Thus, one can study the correlations between pions and charged B mesons with relative ease, and it was argued in Refs. [1] that such correlations should shed light on the corresponding correlations involving neutral B mesons. In this article we wish to explore the relations between charged- and neutral- B correlations with pions more fully.

One might have expected the correlations involving charged and neutral B mesons to be different just by considering the overall charge. For example, in reactions with overall charge zero such as e^+e^- or $\bar{p}p$ collisions, the particles accompanying a B^+ have total charge -1 , while those accompanying a B^0 have total charge zero. Thus, there ought to be more negative pions available for correlation with a B^+ than there are positive pions available for correlation with a B^0 . Nonetheless [1], we expect under normal circumstances the correlations in the non-exotic channels $\pi^+ B^0$ and $\pi^- B^+$ to be identical, and stronger than those in the exotic ones $\pi^- B^0$ and $\pi^+ B^+$, which should also be identical.¹ This argument, reviewed in Sec. II, is a simple consequence of invariance under isospin reflection, or equivalently of the interchange of nonstrange quarks $u \leftrightarrow d$. It should be valid as long as the B mesons are produced by fragmentation from an initial $b\bar{b}$ system which does not exchange flavor quantum numbers with the rest of the production process.

Exchange of quarks with the rest of the system which gives rise to the $b\bar{b}$ pair could invalidate the argument, as discussed in Sec. III. Several other instrumental effects can give an *apparent* difference between charged- and neutral- B correlations. These include the misidentification of charged kaons as charged pions (Sec. IV), the effects of pions in the decay of the associated \bar{B} meson (Sec. V), and the misidentification of the flavor of a neutral B as a result of inadequate particle identification (Sec. VI). We show how to test for each of these effects. Sec. VII concludes.

¹An exotic mesonic channel is one which cannot be reached from a quark-antiquark state

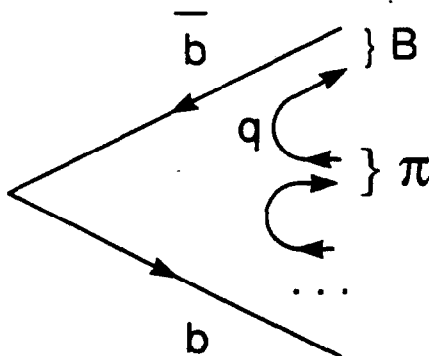


Figure 1: Fragmentation of a $\bar{b}b$ pair into a B meson and other particles in the absence of interaction with quarks in the rest of the system.

II. EQUALITY OF CORRELATIONS WITH PIONS

We consider here only associated production of B hadrons, arising as a result of fragmentation of an initial $\bar{b}b$ pair. In general this pair will arise either from one or more gluons (as in hadronic production), from a photon and one or more gluons (as in photoproduction), from the interference of a virtual photon and a virtual Z as in electron-positron collisions or a Drell-Yan process, or through the decay of a real Z .

As long as the $\bar{b}b$ pair is produced in isolation from other hadrons containing light quarks, the fragmentation of a b quark (Fig. 1) should produce equal “right-sign” correlations between charged pions and B mesons of either flavor. Thus, if the \bar{b} quark in Fig. 1 fragments into a B^0 by producing a quark $q = d$, the next hadron down the chain will contain a \bar{d} . If this hadron is a charged pion, it must be a π^+ . If the \bar{b} fragments into a B^+ by producing a u quark, and the next hadron down the chain is a charged pion, it must be a π^- . The two processes are related to one another by the interchange $d \leftrightarrow u$ and clearly have equal probabilities.

A similar conclusion can be drawn regarding the pions arising from decays of excited “ B^{**} ” resonances. As long as charged and neutral resonances are produced with equal numbers, invariance under reflection of the third component of isospin, I_3 , requires their decays to give equal $\pi^+ B^0$ and $\pi^- B^+$ correlations. The exotic correlations $\pi^- B^0$ and $\pi^+ B^+$ also should be equal.

The decay $Z \rightarrow \bar{b}b$ is an example of a process in which the above conditions are expected to hold, with the pair fragmenting in an isospin invariant manner. A hadronically produced $\bar{b}b$ pair might also fragment in an isospin-invariant manner as long as it does not interact with the rest of the system. For example, if two gluons collide to form a color-singlet $\bar{b}b$ pair, a diagram very similar to Fig. 1 might be expected to account for the hadronization of the heavy quarks. (One should note that a pair of heavy quarks produced in a hadronic collision is produced in a

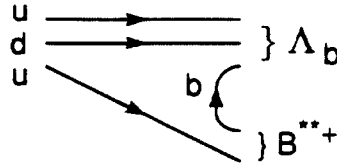


Figure 2: Diffractive dissociation of a proton into a b -flavored meson and baryon, illustrating one source of unequal correlations involving charged and neutral B mesons with charged pions.

color-octet state a significant amount of the time.)

The overall $b\bar{b}$ system (including its fragmentation products, as illustrated in Fig. 1) will be neutral if produced in isolation. The decay products of this system accompanying a neutral B meson then will have zero net charge, while those accompanying a charged B will have a net charge opposite to that of the charged B . One might have expected this circumstance to lead to greater correlations between charged B 's and opposite-sign pions than between neutral B 's and "right-sign" pions (i.e., those leading to non-exotic $B\pi$ states). This can only be true if the *decay products of the associated \bar{B}* are included in the tally of pions. Possibilities for avoiding the effects of these decay products are discussed in Sec. V.

III. INTERACTION WITH THE PRODUCING SYSTEM

A $b\bar{b}$ pair produced hadronically in a color-non-singlet state will exchange color with the rest of the system upon hadronization. Normally this process will proceed in an isospin-invariant manner, via exchange of one or more gluons or isosinglet quark-antiquark pairs. However, there can be exceptions to this rule, an example of which is shown in Fig. 2. A proton diffractively dissociates into a b -flavored baryon and a meson containing a \bar{b} quark. Since the proton has more u quarks than d quarks, the production of charged B^{*+} states is enhanced over that of neutral ones. In this example, B^{*+} decays 2/3 of the time to $\pi^+ B^{(*)0}$ and 1/3 of the time to $\pi^0 B^{(*)+}$, while B^{*0} decays 2/3 of the time to $\pi^- B^{(*)+}$ and 1/3 of the time to $\pi^0 B^{(*)0}$.

One can construct further examples in which an initial $b\bar{b}$ pair produced by one or more gluons picks up quarks from the surrounding medium, as shown in Fig. 3. Since the proton-antiproton system has states of both $I = 0$ and $I = 1$, the rates for production of charged and neutral excited B mesons can differ, and so can the correlations between pions and charged and neutral B 's. One might expect such effects, as well as the diffractive process in Fig. 2, to be least important for central B production at high momentum transfers, and most important for processes in which the heavy quarks are produced at large longitudinal and small transverse momenta.

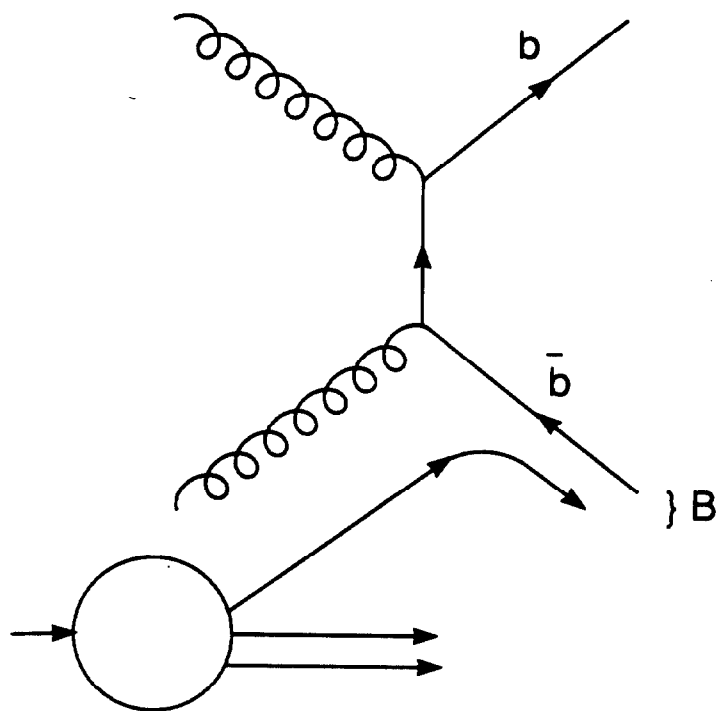


Figure 3: Production of a $b\bar{b}$ pair followed by exchange of quarks with the producing system.

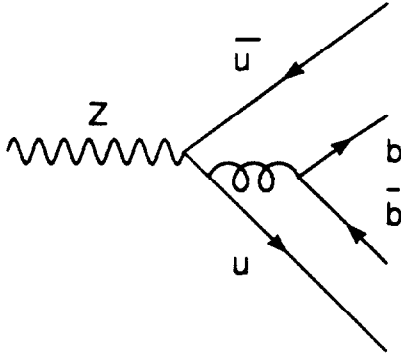


Figure 4: Decay of a Z to $u\bar{u}$ followed by gluonic emission of a $b\bar{b}$ pair.

One expects processes such as those illustrated in Figs. 2 and 3 to be important mainly for hadronic collisions. In order that they contribute in e^+e^- collisions, the light quarks must be produced directly by the electroweak current. For example, a Z decays to $u\bar{u}$ and $d\bar{d}$ pairs with different rates. If a $b\bar{b}$ pair is then produced by gluon radiation, as shown in Fig. 4, there can be apparent violations of isospin reflection symmetry in the fragmentation process.

IV. EFFECTS OF ASSOCIATED CHARGED KAONS

The correlations between charged B 's and charged hadrons nearby in phase space can receive an important contribution from kaons, as shown in Fig. 5. No such correlation with charged kaons of the sort shown in Fig. 5 exists for neutral B 's. (For strange B 's ($B_s \equiv \bar{b}s$) the correlation with charged kaons is expected to be appreciable and, indeed, could be useful in distinguishing B_s from \bar{B}_s at time of production, as first noted in Ref. [2].) In the limit of flavor $SU(3)$ symmetry, in fact, the correlation between a charged B and an oppositely charged kaon would be *equal* to that between a charged B and an oppositely charged pion, effectively *doubling* the signal in comparison with the $B^0\pi^+$ or $\bar{B}^0\pi^-$ correlation.

One can invent other processes in which the particle correlated with the B is a baryon. Instead of the s quark in Fig. 5, one would have an anti-diquark. These examples illustrate the importance of particle identification over a wide range of kinematic configurations. If one can exclude processes such as shown in Fig. 5, the correlation of charged B 's with charged hadrons becomes a much more reliable tool for estimating similar correlations involving neutral B 's.

V. EFFECTS OF PIONS IN DECAY OF ASSOCIATED \bar{B}

The fragmentation "chains" as depicted in Figs. 1 and 5 have very different lengths in high-energy e^+e^- and hadronic collisions. In the decay of a Z^0 to $b\bar{b}$, the heavy quarks and the products of their fragmentation form two distinct jets

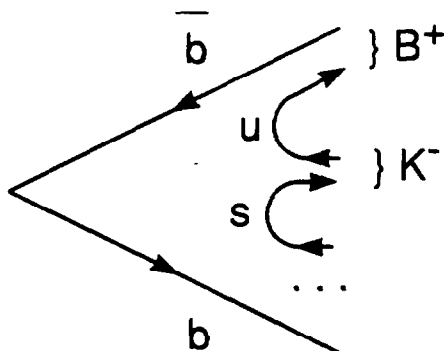


Figure 5: Fragmentation of a \bar{b} quark into a B^+ meson and a K^- .

whose components are highly unlikely to be confused with one another. However, in hadronic collisions, the \bar{b} and b are produced with a spectrum of effective masses which peaks not far above threshold. Thus, unless one takes special care to ensure against it, the decay products of the associated \bar{B} can be among the pions which are correlated with the B of interest.

There are several sources of isospin violation in B decays. (a) The transition $b \rightarrow cud$ changes I_3 by -1 . (b) The transition $c \rightarrow sud$ changes I_3 by $+1$. (c) The decays of charged and neutral D^* 's violate isospin, since the channel $D^{*0} \rightarrow D^+ \pi^-$ is kinematically forbidden. The effects of (a) and (b) largely cancel one another, but (c) can play a significant role in skewing the expected charge distributions of pions in B decays.

The inclusive yield of charged pions in decays of B and \bar{B} mesons has been measured for their sum [as produced at the $\Upsilon(4S)$], but not yet individually [3], and not yet for baryons or antibaryons. The importance of such a measurement is very great, since it allows one to estimate the contamination of correlation signals by b decay products. One could guard against this effect if one could identify the decay vertex of the second b . The pions of interest for performing correlation studies come from the primary vertex and not from detached vertices.

The separation of a B and \bar{B} in phase space is worthy of experimental study both in hadron colliders and in electron-positron colliders at various center-of-mass energies. At $B\bar{B}$ threshold, in the decay of the $\Upsilon(4S)$, there are no other pions. Above threshold for single-charged-pion production, in a reaction such as $e^+e^- \rightarrow B^+ \pi^- \bar{B}^0$ [4], the B with which the charged pion is associated is clearly ambiguous, though both correlations are "right-sign." In an event such as $e^+e^- \rightarrow B^+ \rho^0 B^- \rightarrow B^+ \pi^+ \pi^- B^-$ or $e^+e^- \rightarrow B^0 \rho^0 \bar{B}^0 \rightarrow B^0 \pi^- \pi^+ \bar{B}^0$ the "wrong-sign" correlation may be strongest (using some measure such as pion- B effective mass), depending on the decay angle of the ρ^0 . For large effective mass of the produced $b\bar{b}$ pair, there will still be some "wrong-sign" correlations as a consequence of effects like ρ^0 decay. However, with the important exception of correlations [5] between

one B and the decay products of the other, all these effects should be invariant under the isospin reflection transformation $u \leftrightarrow d$.

In order to specify the separation of a B and \bar{B} produced in hadronic collisions, it would be useful to know the spectrum of effective masses of $b\bar{b}$ systems produced in these collisions. Related information would be provided by the multiplicities of charged pions accompanying the reactions $e^+e^- \rightarrow b\bar{b}$ as center-of-mass energies are varied from threshold to M_Z .

VI. IDENTIFICATION OF NEUTRAL K^* FLAVOR

Neutral B 's of identified flavor have been fully reconstructed in many different decay modes [3]. However, the only easily accessible mode in hadron colliders up to now has been $B^0 \rightarrow J/\psi K^{*0}$ because of the ease of identification of the J/ψ . One then identifies the flavor of the K^{*0} through its decay to $K^+\pi^-$.

If particle identification is not efficient, a $K^+\pi^-$ system can be confused with $K^-\pi^+$, especially if only a fraction of the available phase space is sampled. To see this, let p_π and p_K be the 4-momenta of the pion and kaon, and let them have a squared-invariant mass $m_{K\pi}^2 = (p_\pi + p_K)^2$. If the pion and kaon are interchanged, the error in the squared mass is approximately

$$\Delta m^2 \equiv m_{\text{incorrect}}^2 - m_{\text{correct}}^2 \simeq (m_K^2 - m_\pi^2)(\vec{p}_K^2 - \vec{p}_\pi^2)/(|\vec{p}_\pi||\vec{p}_K|) \quad (1)$$

Thus, one requires very asymmetric decay configurations in order to see a broadening of a K^* peak as a result of the wrong assignment of a pion and kaon. If any circumstances limit the momenta of pions and kaons accepted in the data sample to a narrow range, the potential for confusion is great.

It is desirable to calibrate one's efficiency for detecting the flavor of neutral K^* 's. Charmed particle decays can be very helpful in this respect. Charmed particle decays involving neutral K^* 's include $D^0 \rightarrow \bar{K}^{*0}\pi^+\pi^-$ and $D^+ \rightarrow \bar{K}^{*0}\pi^+$. The flavor of the decaying D^0 can be identified through the chain $D^{*+} \rightarrow \pi^+D^0$, with emission of a characteristic soft pion. The D^+ decay is self-tagging. In a hadron collider, charm signals can be found in channels such as $\bar{B} \rightarrow D^{(*)}\ell\nu_\ell$, which can be studied using high-transverse-momentum leptons.

Because $J/\psi K^{*0}$ events are so rare, it may be possible to increase the data sample by not requiring full reconstruction of the B meson. For instance, a detached J/ψ is guaranteed to originate in a b quark decay, and any mode of the type $J/\psi K^{*0}X^0$ or $J/\psi K^{*+}\pi^-X^0$, where all particles come from the same secondary vertex, reveals the flavor of the decaying neutral B meson. Neutral pions and photons can be missed, but one must be more careful about neutral strange particles that escape detection. If K/π separation is available, one can use in addition the mode $J/\psi K^+\pi^-X^0$, where the kaon and pion are not necessarily in a K^{*0} . In order to know whether these semi-inclusive modes are useful, it would help to know the branching ratios for $B^0 \rightarrow J/\psi K^{(*)}$, where $K^{(*)}$ denotes the higher kaon resonances. Such information can be provided by present detectors such as CLEO.

VII. CONCLUSIONS

The correlations of charged pions with neutral B mesons is a potential source of information on the flavor of the produced heavy meson, which in turn can be useful in searching for CP-violating asymmetries. We have shown that correlations with *charged* B mesons can provide a helpful calibration of this method, but only if potential differences between the two cases are taken into account. The fragmentation of a $b\bar{b}$ pair produced in isolation would not be expected to lead to such differences, as a result of symmetry under the isospin reflection $I_3 \rightarrow -I_3$.

A genuine physics difference between the behavior of charged and neutral B 's can arise if the fragmentation of a b quark involves other quarks "picked up" from the producing system. This effect might be sensitive to the transverse momentum and pseudorapidity of the B . For instance, it could well be an important feature of production at large longitudinal and small transverse momenta, but might be less important for central collisions with high transverse momenta.

Several other effects can give rise to apparent differences between charged and neutral B 's which are in fact spurious. These include the misidentification of kaons produced nearby in phase space, the confusion of B decay products with pions from the primary production vertex, and the interchange of pions and kaons in forming neutral K^* 's. We have suggested several ways in which one might test for such effects.

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